Coastal Engineering Technical Note

REMOTE SENSING TECHNIQUES FOR MEASURING OCEAN WAVES

PURPOSE: To provide an overview of principles involved in remote sensing of coastal wave data using radar and to summarize several systems that are either fully or quasi-operational. The summaries are intended to aid Corps Districts in selection of remote sensing techniques for coastal wave data collection.

BACKGROUND: Wave measurement technology has progressed rapidly in the last decade. Remote sensing techniques have advanced from concepts to fully-operational systems providing oceanographers and coastal engineers with a wealth of ocean wave information. The measurement of wave characteristics, such as height, length, and direction using electromagnetic (EM) waves is one of the latest developments in the field of ocean wave studies. Since Crombie (1955) first deduced the physical mechanism responsible for sea scatter of EM energy, numerous approaches have been taken toward producing a viable sensor for measuring ocean wave characteristics. Techniques range from ground-based, high-frequency (5 to 100 MHz) coastal radars to spaceborne microwave (0.1 to 100 GHz) systems.

To give a better appreciation for the information these systems provide, some basic concepts on the interaction of electromagnetic and ocean waves are provided, followed by a brief review of various sensors.

BASIC CONCEPTS:

A. *Scattering Processes*

The basic interaction between electromagnetic and ocean waves is backscattering. When EM waves impinge upon a rough ocean surface, a certain amount of incident energy is reflected, or scattered, back to the sensor. This return signal contains information about the ocean surface. The two basic processes, or mechanisms, responsible for backscatter of EM energy are specular reflection and Bragg scattering (see Figure 1).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAR 1985**	2. REPORT TYPE	3. DATES COVERED **00-00-1985 to 00-00-1985**

4. TITLE AND SUBTITLE **Remote Sensing Techniques For Measuring Ocean Waves**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U. S. Army Engineer Waterways Experiment Station,Coastal Engineering Research Center,P.O. Box 631,Vicksburg,MS,39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

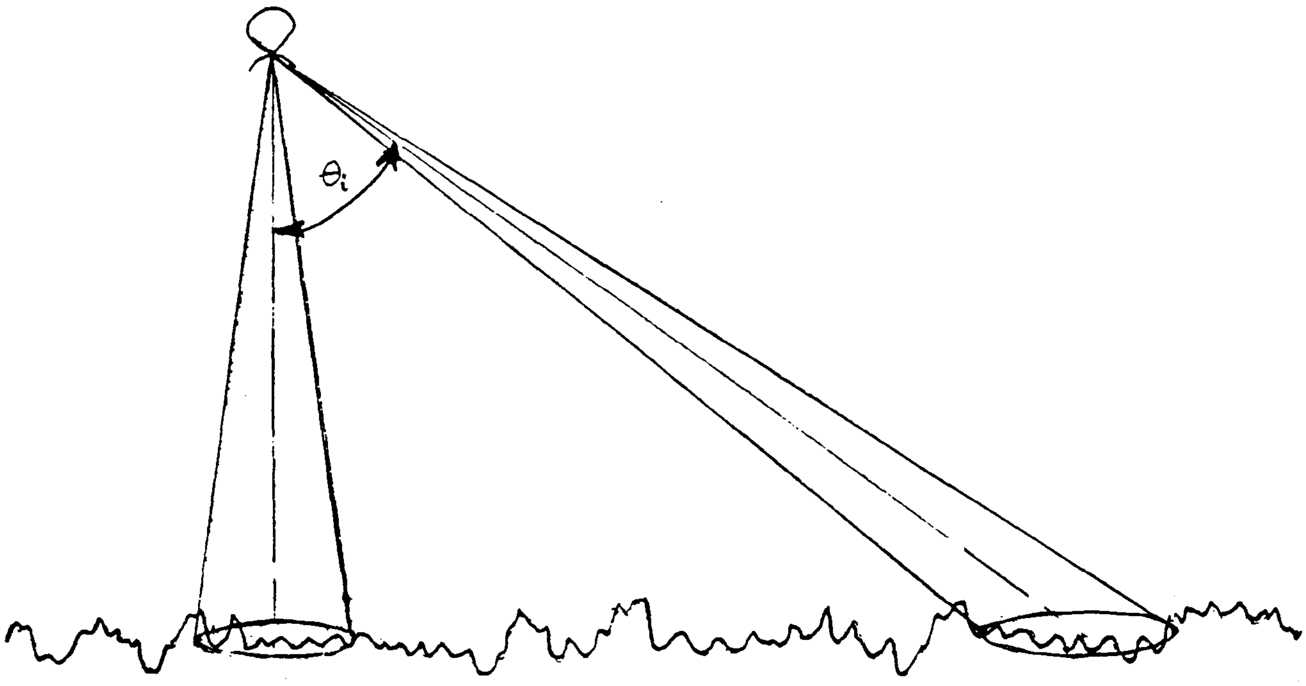
13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18



(a) Specular reflection dominant (b) Bragg scattering dominant

Figure 1 . Basic backscattering processes (after Huang 1982)

In specular reflection, the energy is reflected by a facet or a surface perpendicular to the incident energy. The degree of specular reflection is controlled by the angle-of-incidence with respect to the vertical. Radars that look straight down, called nadir-looking radars, rely on this mechanism for their signal.

As the incident angle increases beyond a certain limit, defined by the surface slope, the Bragg scattering mechanism begins to dominate. In simple terms, the scattering is generated by those ocean waves that, as a result of their wavelengths, provide constructive reinforcement of the return signal at the radar antenna. These waves satisfy the "Bragg resonant" condition given by

$$\lambda_r = 2 \lambda_w \text{Sin } \theta_i \tag{1}$$

where λ_r and λ_w are the radar and ocean wavelengths respectively, and θ_i is the incidence angle with respect to the vertical. This condition implies that at grazing incident angles, the return signal is provided by ocean waves that have wavelengths roughly one-half the radar wavelength.

B. *Measurement Techniques*

Two techniques exist for extracting information from backscattered radar energy. These techniques are basic to any EM remote sensing system.

1. *Ranging*

The basic function of a radar is to measure the distance between the radar and the target. By measuring the elapsed time between pulse transmission and return, the range is determined by the following equation:

$$R = \frac{ct}{2} \tag{2}$$

where R is the range to the target, c is the speed of light (3×10^8 m/sec), and t is the measured time.

Individual wave heights are difficult to measure with ranging techniques. To measure wave height, the radar footprint, or illuminated surface area, must be small compared to the ocean wavelength. The footprint size is determined by range and radar beamwidth, which is a function of antenna size. For example, for a real aperture system, radar beamwidth and aperture are related by

$$\phi = 1.2\ \lambda_r/D \tag{3}$$

where ϕ is the radar beamwidth, and D is the antenna aperture. Thus, the narrow beamwidth required for individual wave height measurements can be achieved only with a large antenna.

2. *Doppler Effect*

If there exists some relative motion between the radar and the target, the return signal exhibits a shift in frequency. The "Doppler" shift is directly related to the relative velocity and inversely proportional to the radar wavelength according to

$$f_d = 2V/\lambda_r \tag{4}$$

where f_d is the Doppler frequency shift, and V is the relative velocity. The return signal, displayed as a Doppler frequency spectrum, is analyzed to provide information on both surface currents and waves.

C. *Output*

Although the techniques involved in remote sensing with radar are

relatively simple, a wide variety of implementations exist. Output is often used to classify radars as either imaging or non-imaging.

Most imaging radars are side-looking devices which produce images that show many of the same characteristics as aerial photos. The image, which represents varying intensity of the return signal, is displayed as light and dark patches representing wave crests and troughs. Visual examination of this imagery can provide information on wave lengths, direction, refraction, diffraction, and wave-current interactions. Automatic processing by optical or digital Fourier transforms provides spectral information as well.

Non-imaging radars produce some other easily measurable and identifiable output that can be converted to the desired product. This output may be a voltage time series from which wave information is extracted.

AVAILABLE SENSORS: A summary of remote sensing systems for measuring ocean waves is given in Table 1. Each system is discussed briefly in the following paragraphs.

Table 1

Summary of Remote Sensing Systems for Measuring Ocean Waves (after Dean 1982)

	Sensor	SLAR	SAR	Coastal Wave Imaging Radar	CODAR	ROWS	Δ k	SCR
WAVE PARAMETERS	Status	Operational	Operational	Operational	Operational	Operational	Developmental	Operational
	Height	No	(1)	No	Yes	Yes	Yes	Yes
	Length	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Direction	Yes	Yes	Yes	Yes	No	Yes	Yes
	Spectrum	Directional Wavenumber Spectrum	Directional Wavenumber Spectrum	Directional Wavenumber Spectrum	Directional Waveheight Spectrum	1-D Waveheight Spectrum	Directional Waveheight Spectrum	Directional Waveheight Spectrum
	Spatial Coverage	1 km swath	Aircraft 1 km swath	Up to 5 km radius	40 km radius	Several sq Meters	2-3 km Radius	Swath width = 1/2 aircraft altitude
	Cell Size Resolution	Depends on range	Aircraft 3 m spatial resolution	15 m range resolution	5 km spatial resolution	Several sq Meters	90 m Range Resolution	.5 -2.0 km^2 cell size
	Platform	Aircraft	Aircraft/ Satellite	Land-based tower	Land-based	Land-based tower	Land-based tower	Aircraft
	System Cost	Expensive	Very Expensive	\$50 K	\$150 K	\$50 K	\$100 K	\$500 K
	Cost/ Typical Data Set	Moderate	\$1000 per 5 km x 5 km patch	\$100	Low	Low	Low	\$2700/hr aircraft flight time
	Comments	Limited spatial resolution. Available through Dept. of the Army.	Increased resolution: more expensive than SLAR.	Present Corps capability. Available for field use.	Present Corps capability. Currently undergoing field demonstrations.	Possible future Corps capability. Uses include monitoring waves during dredging operations.	Provides data at scales between ROWS and CODAR. Uses could include monitoring waves in harbors and entrances	Aircraft out of Wallops Is., VA. Expensive for remote study sites. Data acquisition quick.

(1) Theoretically possible, but no algorithm developed as yet.

A. *Side-Looking Airborne Radar (SLAR)*

SLAR is a real-aperture imaging microwave radar. It generates photo-like images of wave patterns by recording the backscatter properties of the ocean surface. The relatively large antenna is carried on the underside of an aircraft, directing a narrow, fan-shaped beam of energy at right angles to the flight path. The return signal is recorded over a specific time period and sliced into small segments, each representing a distance from the aircraft. The signal strength is averaged over each time increment, and the result is an averaged radiance at each range. Spatial resolution is limited by the radar beamwidth which, in turn, is limited by the antenna size. This "real aperture" limitation led to the development of the synthetic aperture radar. Optical or digital processing of SLAR imagery can provide a directional wave number spectrum which details information on wavelength and direction but provides no information on wave height.

B. *Synthetic Aperture Radar (SAR)*

SAR is a synthetic aperture imaging microwave radar. Although the output is similar to that of the SLAR, the image-forming mechanism is more complex. To improve the spatial, in particular along-track, resolution, a method was developed that makes a relatively short antenna with a wide beam behave like a very long antenna with a narrow beam. This principle is called "synthetic aperturing." Spatial resolution is independent of range, a result that makes SAR, via both airborne and spaceborne platforms, a leading candidate for obtaining nearly synoptic directional wave information on a global basis. The expense involved with deploying an aircraft or satellite as well as the complex data processing required are major drawbacks.

In addition to providing a directional wave number spectrum, SAR has also shown promise in the tracking of oceanic eddies and in mapping bathymetric features. Wave height information, although theoretically possible, is not yet obtainable.

C. *Coastal Wave Imaging Radar*

Coastal wave imaging radar utilizes a conventional marine navigation radar mounted on shore. A plan position indicator (PPI) scope displays the return signal, generally referred to as sea clutter, in the form of light and dark patches that parallel the wave crests. The image is then photographed at selected intervals. These photos can be analyzed manually to provide wave-

length and direction or automatically by digitizing and processing with a digital Fourier transform. This provides a directional wave number spectrum for nearshore (3 nautical-mile-range maximum) wave fields. No wave height information is available from this system.

D. *Doppler Radar*

Doppler radars are side-looking, non-imaging devices that measure the Doppler effect, or frequency shift of the returned signal, produced by the relative motion between the radar and the target. Doppler radars can be fixed, shorebased systems or operated from a moving platform. Several are discussed.

1. *Coastal Ocean Dynamics Application Radar (CODAR)*

CODAR is a high frequency (25 MHz), ground-based, non-imaging, Doppler radar. The basic principle behind CODAR is a strong Doppler effect on the Bragg-scattered signal at both first and second order.

An examination of the Doppler frequency spectrum of the return signal shows two distinct regimes. The first-order regime, or echo, is characterized by a sharp and distinct peak at a frequency corresponding to the ocean wave satisfying the Bragg resonant condition. A deviation from this frequency is the result of advection by an underlying surface current.

The second-order regime is the continuum portion of the spectrum and contains more information on the ocean surface properties. This portion is caused by scatter from all ocean waves and provides, after analysis, the directional wave height spectrum.

CODAR, as a wave measuring system, covers an area within approximately a 36-km radius of the radar site with spatial resolutions of the resulting wave spectrum of 5 km. If the water depth in the coverage area is shallow relative to the wavelength of the water waves (ratio of water depth to wavelength less than 1/2), then refraction theory must be used in analysis of the radar data.

2. *Single Frequency Remote Orbital Wave Scatterometer (ROWS)*

The single frequency scatterometer is a compact, transportable, side-looking, shore-based microwave radar. By using a narrow beam and short ranges, the radar footprint is kept small compared to the dominant ocean wavelength. It is therefore capable of measuring, via the Doppler frequency shift, both the surface current and the large wave orbital velocity.

Knowledge of the dominant wave frequency coupled with the measured orbital velocity provides the dominant wave height. Direction information is not provided. In fact, prior knowledge of the dominant wave direction is assumed.

3. *Dual Frequency* (Δk) *Wave Spectrometer*

The Δk wave spectrometer is a non-imaging, side-looking microwave radar with an output similar to that of CODAR. Two closely spaced frequencies are transmitted and scattered by ocean waves which are in Bragg resonance with the difference, or "beat," frequency $(f_1 - f_2 = \Delta k)$. Thus, by varying the difference in transmitted frequencies, together with the azimuth of the antenna axis, a full directional wave height spectrum can be determined. This system is developmental at present and has been successfully tested from both fixed and moving platforms.

E. *Surface Contouring Radar (SCR)*

The SCR is a non-imaging, ranging device that uses a very narrow beam to measure the distance between the platform (aircraft) and the ocean surface. A pencil beam is scanned across the ground track to measure the range to 51 evenly spaced points providing a real-time topographic map of the surface. Application of a two-dimensional Fast Fourier Transform (FFT) produces a directional wave height spectrum for a swath width of roughly one-half the aircraft altitude and length of approximately 5 km.

CONCLUSIONS: The land-based systems described in this Tech Note are the most feasible for routine wave data collection. Once purchased, data collection is relatively inexpensive, and the portability of these systems provides ease of operation even in remote sites. These systems can provide, on scales of a few square meters to hundreds of square kilometers, much needed coastal wave and current data in virtually any weather. The airborne sensors, such as SAR and SCR are more expensive but can be powerful and useful tools for short-term observation of wave conditions which are homogeneous over the spatial coverage area.

AVAILABILITY: Present Corps capabilities consist of a coastal wave imaging radar and a CODAR system. The imaging radar is fully-operational, with automatic image processing capabilities currently under development. More detailed information on the imaging radar can be found in Mattie and Harris (1979). The CODAR system, a recent acquisition, will be undergoing field demonstrations over the next year.

Plans are currently under way to obtain a single frequency ROWS for application to coastal waves and currents. This system, as designed for surface current measurements, is detailed in CERC CETN-I-7 (9/84). The development of the Δk spectrometer by the Naval Research Laboratory is being closely monitored as a possible future tool for District applications.

SLAR is available, through various Department of the Army organizations, for use by all Corps field offices. Further information may be found in CERC CETN-I-9 (9/81). The SCR, developed at NASA's Goddard Space Flight Center, Wallops Island, Virginia, is available on a lease basis, but the $2,700/hr price tag for aircraft flight time makes it prohibitively expensive for sites far from Wallops Island. SAR availability is limited as a result of the high system cost and complexity. Inquiries concerning SAR overflights for District needs should be directed to the appropriate Remote Sensing Coordinator.

ADDITIONAL INFORMATION: For further information, contact Mr. David Driver, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Research Division, Coastal Oceanography Branch, at (601) 634-3040

REFERENCES:

Crombie, D. D. 1955. "Doppler Spectrum of Sea Echo at 13.56 MC/S," Nature, Vol 175, pp 681-682.

Dean, R. G. 1982. "Summary: Symposium and Workshop on Wave-Measurement Technology," Measuring Ocean Waves: Proceedings of a Symposium and Workshop on Wave-Measurement Technology, National Academy of Engineering, Washington, D. C., pp 1-13.

Huang, N. E. 1982. "Survey of Remote Sensing Techniques for Wave Measurement," Measuring Ocean Waves: Proceedings of a Symposium and Workshop on Wave-Measurement Technology, National Academy of Engineering, Washington, D. C., pp 38-79.

Mattie, M. G., and Harris, D. C. 1979. "A System for Using Radar to Record Wave Direction," CERC Technical Report No. 79-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center. 1981. "Radar Imagery of Waves," CETN-I-9, Vicksburg, Miss.

US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center. 1984. "Surface Current Measurements Using a Microwave Scatterometer," CETN-I-7, Vicksburg, Miss.